Nitrogen Removal Technologies for Meeting Nitrogen Load Reductions in the Chesapeake Bay Watershed

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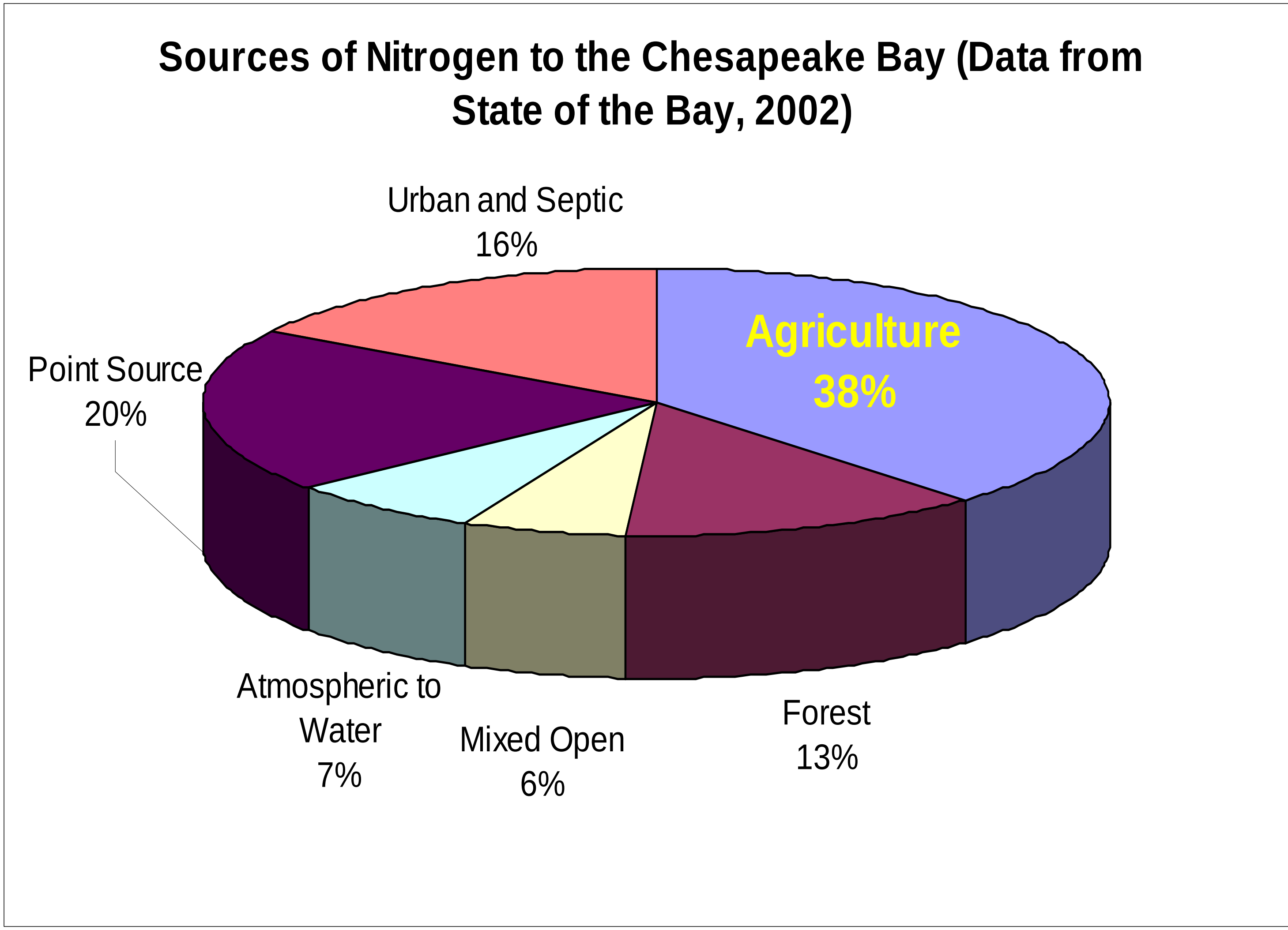
Today, I will:

- Review the problem
- Review nitrogen metabolism
- Discuss basic design principles of nitrogen removal
- Review nitrogen removal technologies
- Some research efforts at Virginia Tech that relate to this topic

Point sources accounted for 20% of the nitrogen load to the Bay in 2002



Why do we need to remove nutrients?

Algae composition = $C_{106}H_{263}O_{110}N_{16}P$

1 g N yields 16 g algae
1 g P yields 114 g algae

http://www.nos.noaa.gov/education/kits/estuaries/

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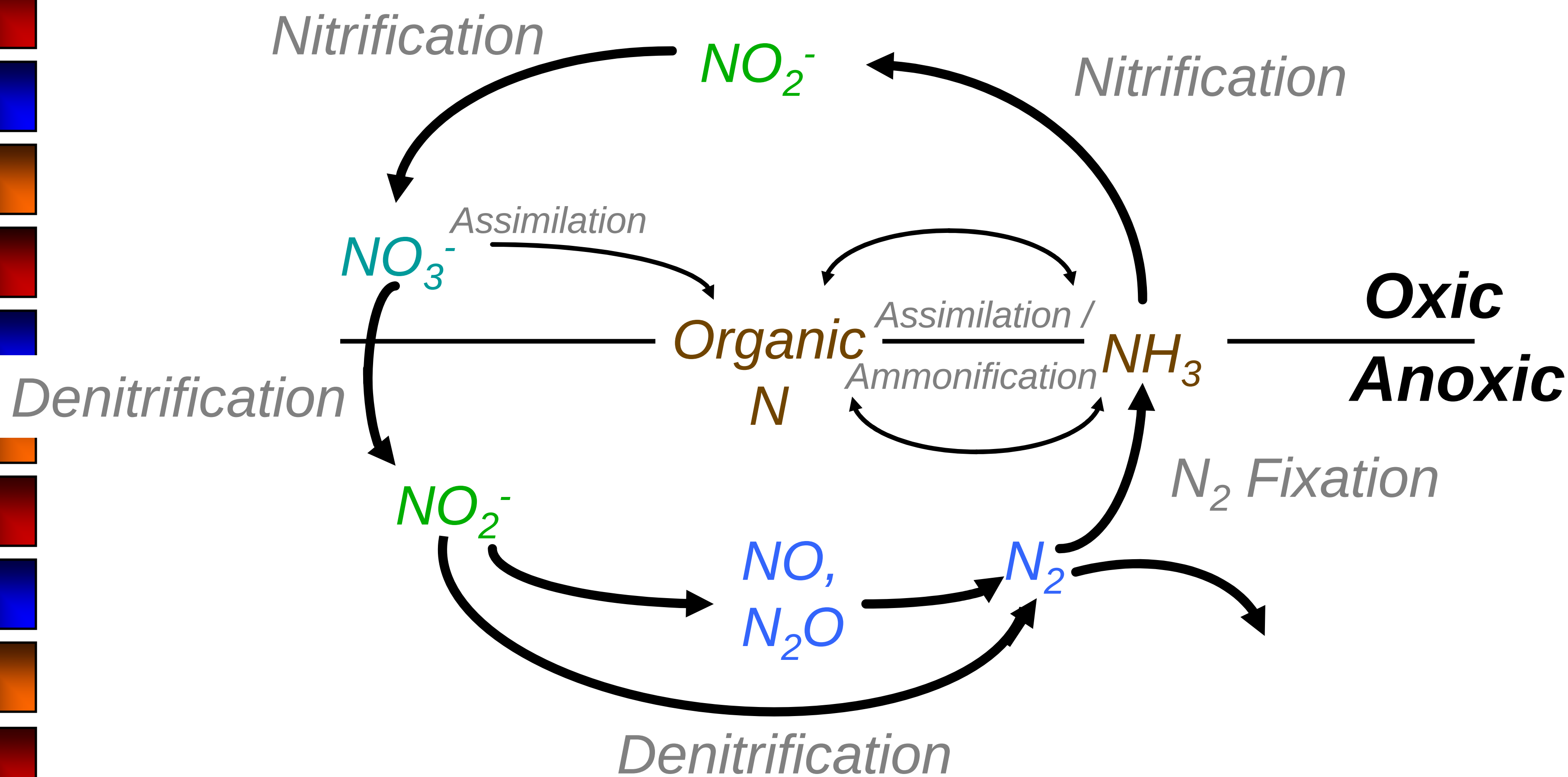
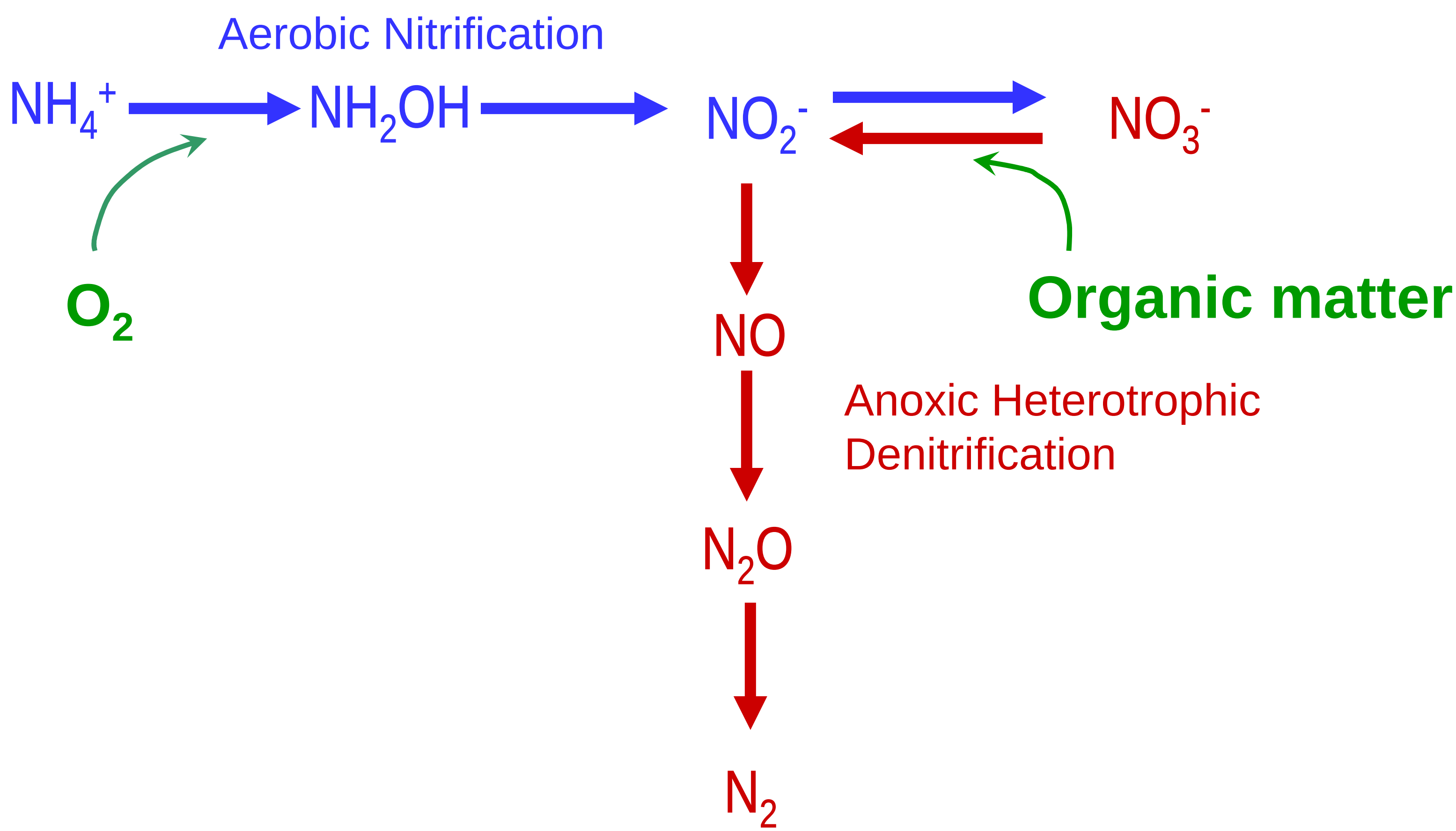
The Nitrogen Cycle



Adapted from Madigan et al., 1997

Conventional N removal involves coupling aerobic nitrifiers with anoxic denitrifiers



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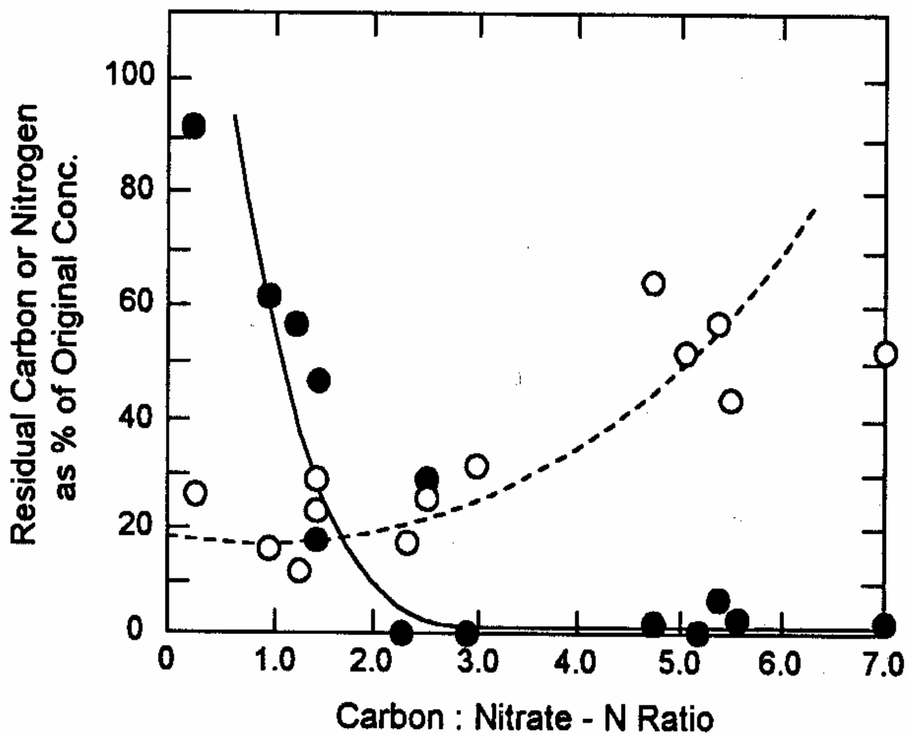
Need to optimize organic carbon loading to achieve high quality effluent



Grady, Daigger and Lim, 1999

Figure 6.12 Effect of S_{SO}/S_{NOO} (expressed as C/N ratio) on the removal of carbon (○) and nitrogen (●) in a CSTR operated under anoxic conditions. (From K. Wuhrmann, Discussion of 'Factors affecting biological denitrification of wastewater' by R. N. Dawson and K. L. Murphy. *Advances in Water Pollution Research, Jerusalem, 1972*, 681–682, 1973. Reproduced by permission of Dr. K. L. Mechsner.)

Need to optimize organic carbon loading to achieve high quality effluent

Table 11.3 Relationship Between Expected Biological Nitrogen Removal Efficiency and Influent Organic Matter to Nitrogen Ratios

Nitrogen removal efficiency	COD/TKN	BOD_5/NH_3-N	BOD_5/TKN
Poor	<5	<4	<2.5
Moderate	5–7	4–6	2.5–3.5
Good	7–9	6–8	3.5–5
Excellent	>9	>8	>5

Grady, Daigger and Lim, 1999

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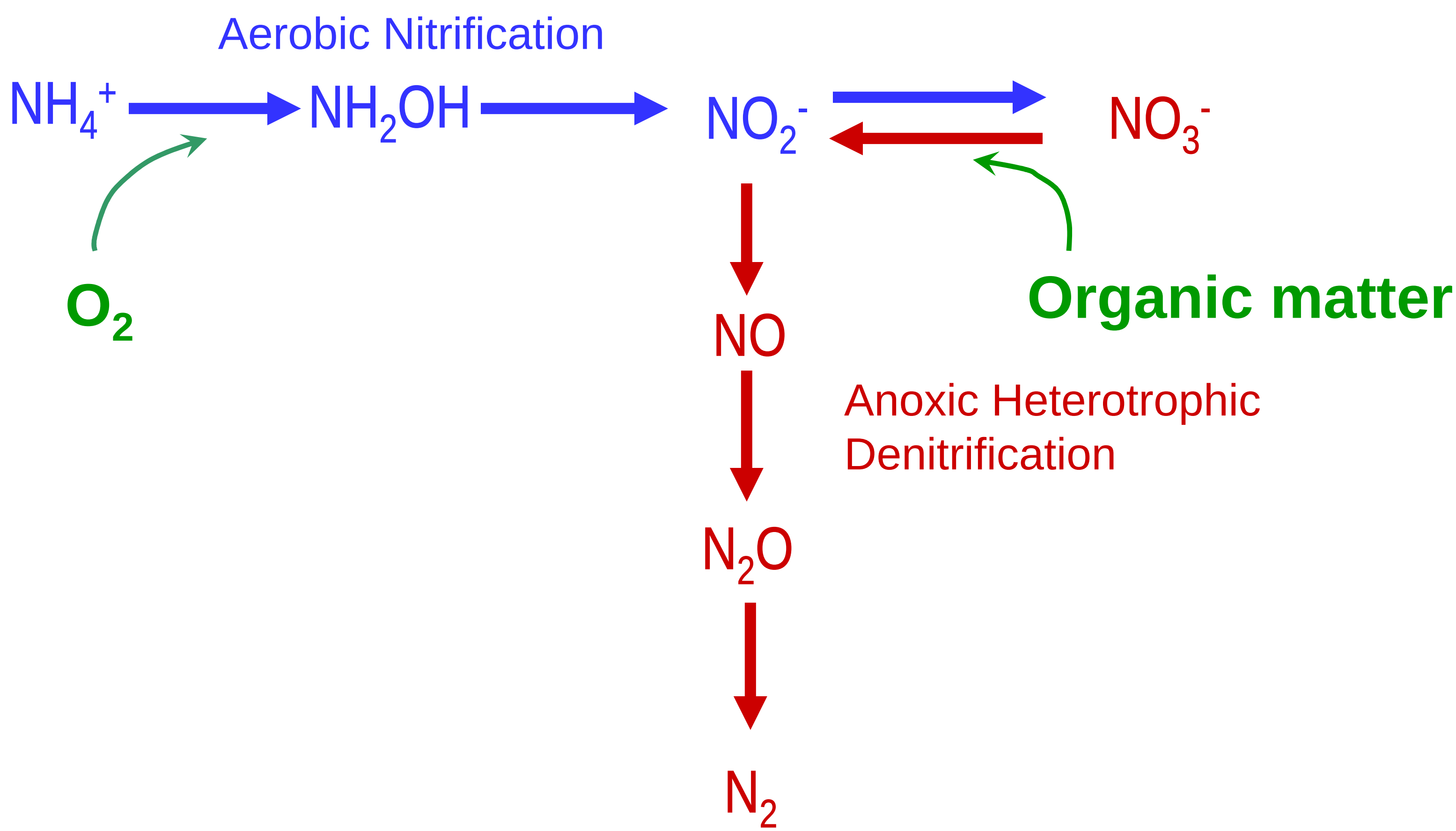
Conventional N removal involves coupling aerobic nitrifiers with anoxic denitrifiers



Nitrification

- Process implications from kinetics
  - Nitrifiers are slow growers (defines SRT)
  - Nitrification tends to be an “all-or-none” phenomenon (on or off)

Sludge age must be selected to ensure nitrification

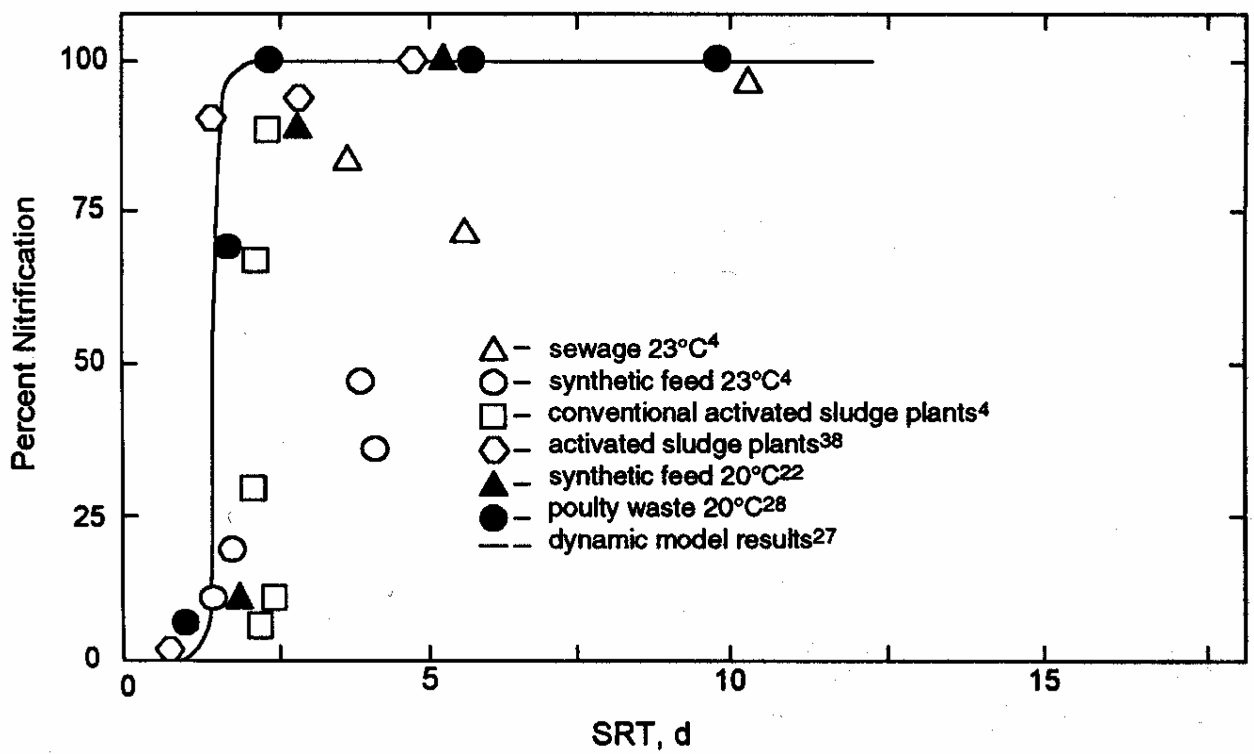


Figure 6.4 Effect of SRT on the steady state nitrification performance of a CSTR. The reference numbers refer to the sources of the data. (Adapted from Poduska and Andrews.[27])

Grady, Daigger and Lim, 1999

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Nitrification

- Process implications from kinetics
  - Nitrifiers are slow growers (defines SRT)
  - Nitrification tends to be an “all-or-none” phenomenon (on or off)
  - Kinetics of growth are very sensitive to:
    - temperature
    - dissolved oxygen concentration
    - pH (optimal 7.5 - 8.6)
    - C:N ratio
    - inhibiting compounds

Dissolved oxygen must be sufficient to ensure complete nitrification

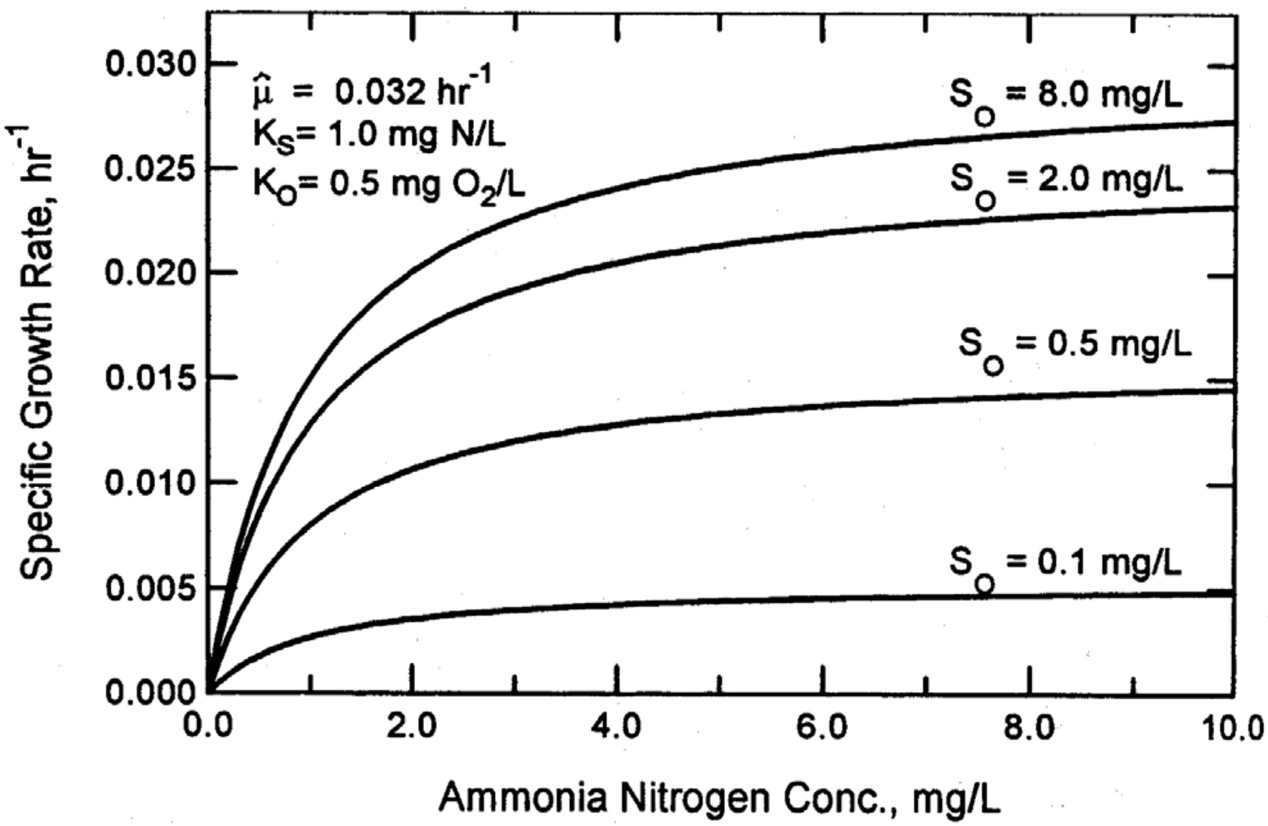

Figure 3.3 Double Monod plot showing the effects of both ammonia nitrogen and dissolved oxygen concentrations on the specific growth rate of autotrophic nitrifying bacteria. The parameter values given were used to construct the curves with Eq. 3.46.

Grady, Daigger and Lim, 1999

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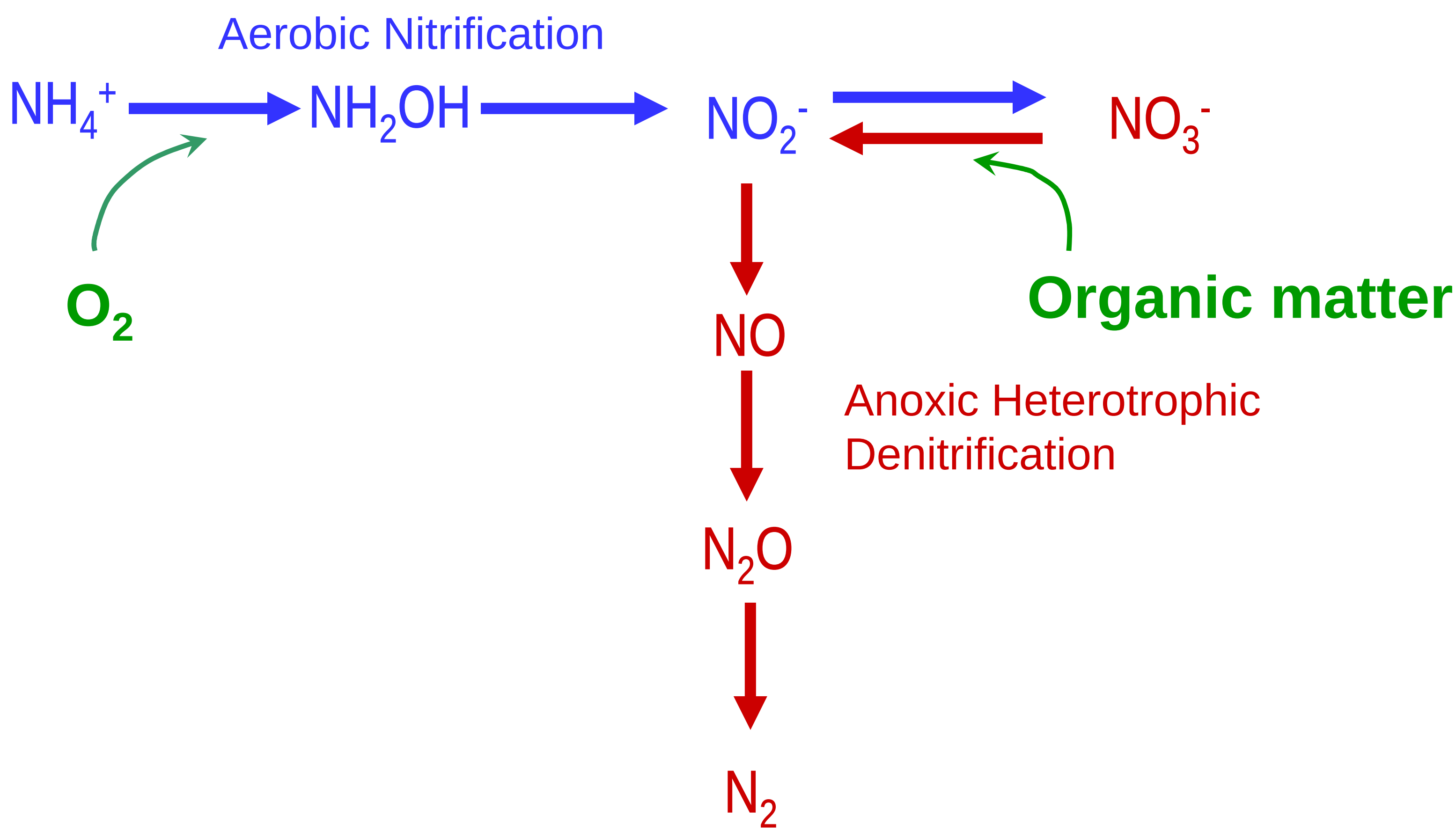
Conventional N removal involves coupling aerobic nitrifiers with anoxic denitrifiers



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Conventional nitrogen removal can be achieved through a range of treatment configurations

- Single sludge systems
- Post bioreactor filtration systems
- Integrated fixed film/activated sludge systems
- Fixed film systems

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MLE Process

- Total N: 4 to 8 mg/L
- Anoxic volume:Aerobic volume ~ 30:70

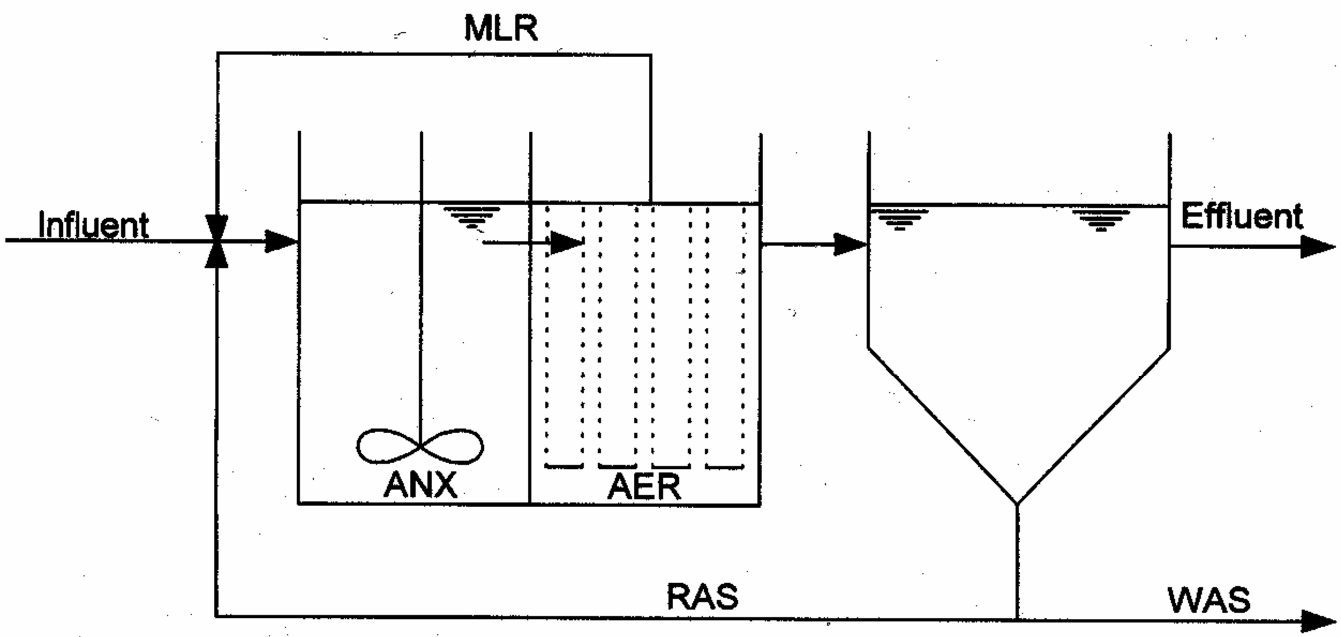

Figure 11.4 Modified Ludzak–Ettinger (MLE) process. A system with an anoxic selector has the same process flow diagram, but with a smaller anoxic zone.

Grady, Daigger and Lim, 1999

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Four-Stage Bardenpho

- Improved N removal with second stage
- Reliable Total N to 3 mg/L unlikely

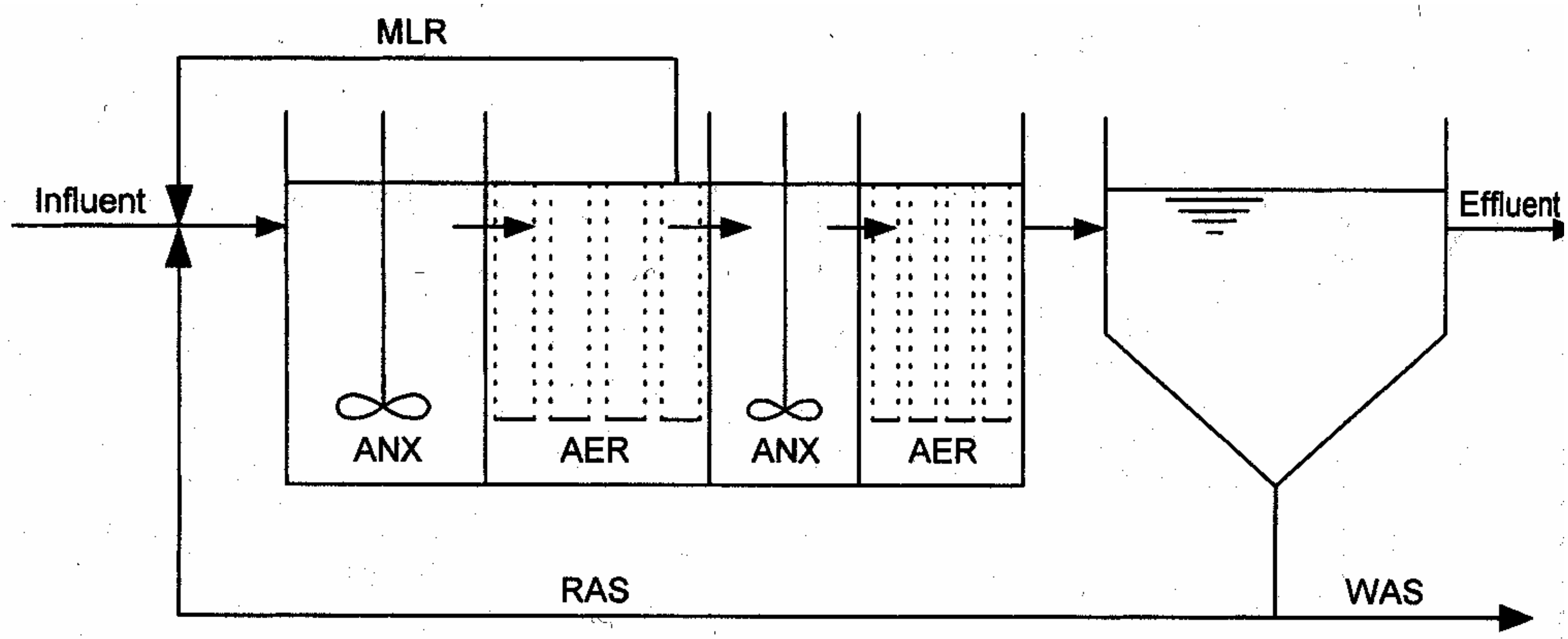

Figure 11.5 Four-stage Bardenpho process.

Grady, Daigger and Lim, 1999

Virginia Initiative Plant (VIP)

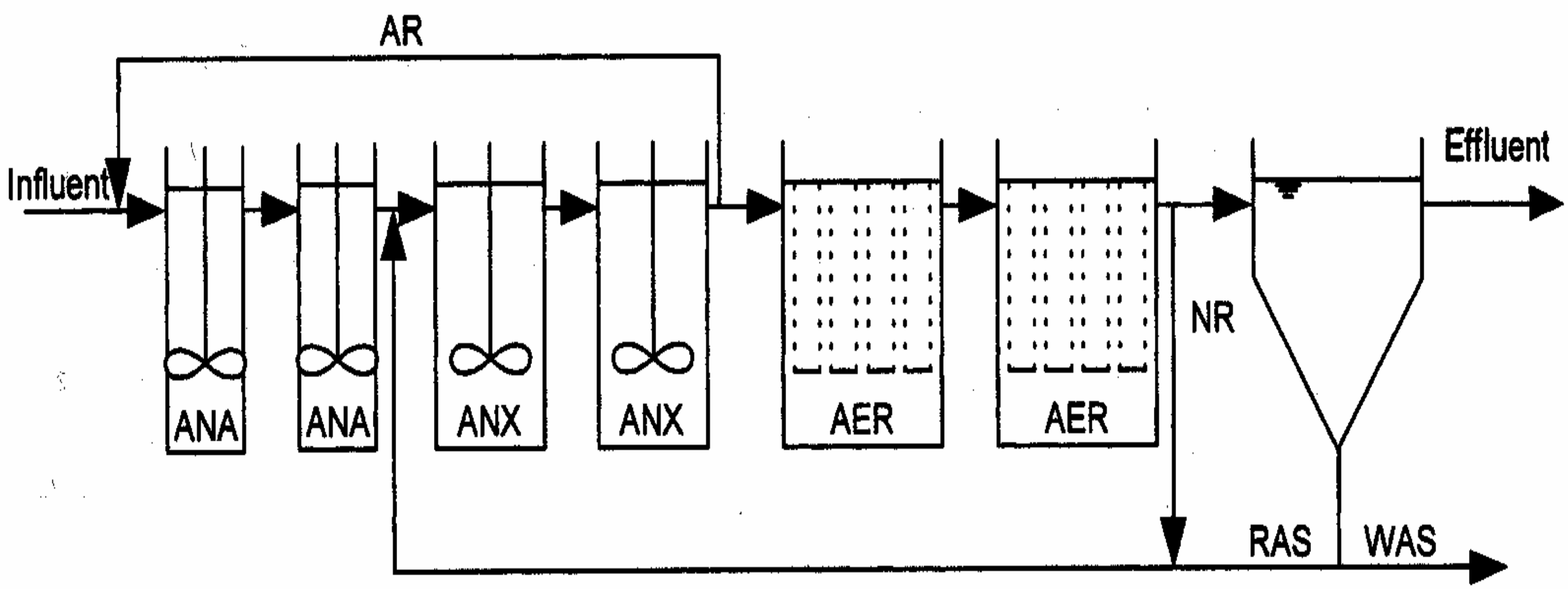

Figure 11.13 VIP process.

Grady, Daigger and Lim, 1999

Separate stage single sludge N removal process

- 3 to 5 day SRT
- Cost of supplemental organic source must be considered
- Common retrofit strategy

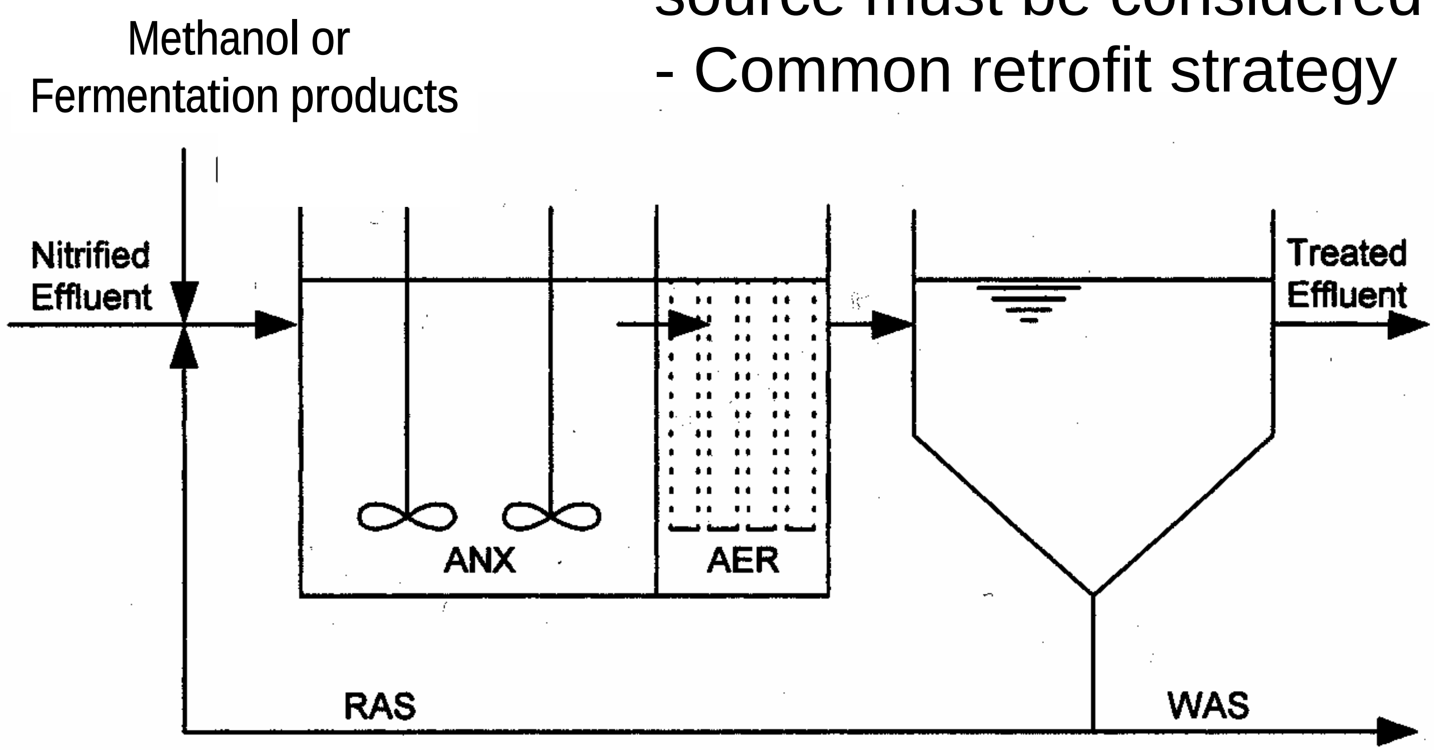

Figure 11.7 Separate stage suspended growth denitrification process.

Grady, Daigger and Lim, 1999

Fixed film denitrification or nitrification can be used as well

ODI Biofor Systems

cBOD removal

Nitrification

Factors that Affect BNR

- SRT
- Wastewater BOD_5/Nutrient ratios
- Organic matter composition
- Effluent TSS
- Environmental Factors
- - Temperature
- - pH
- - Dissolved O_2 concentration
- Sludge Handling Practices

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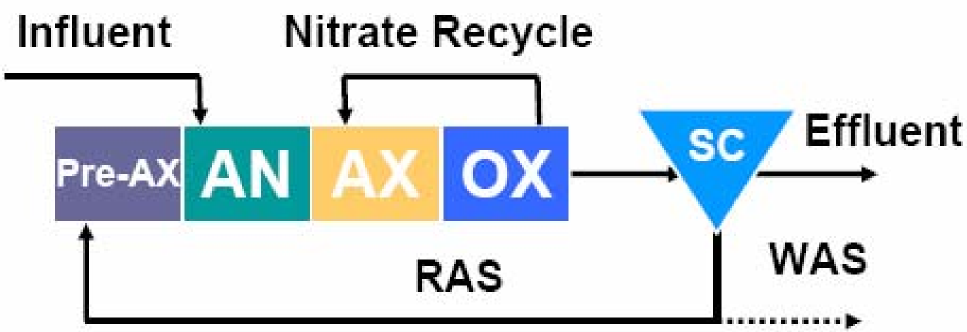
Consider the impact of effluent TSS

Consider a floc of bacteria: $C_5H_7O_2N$

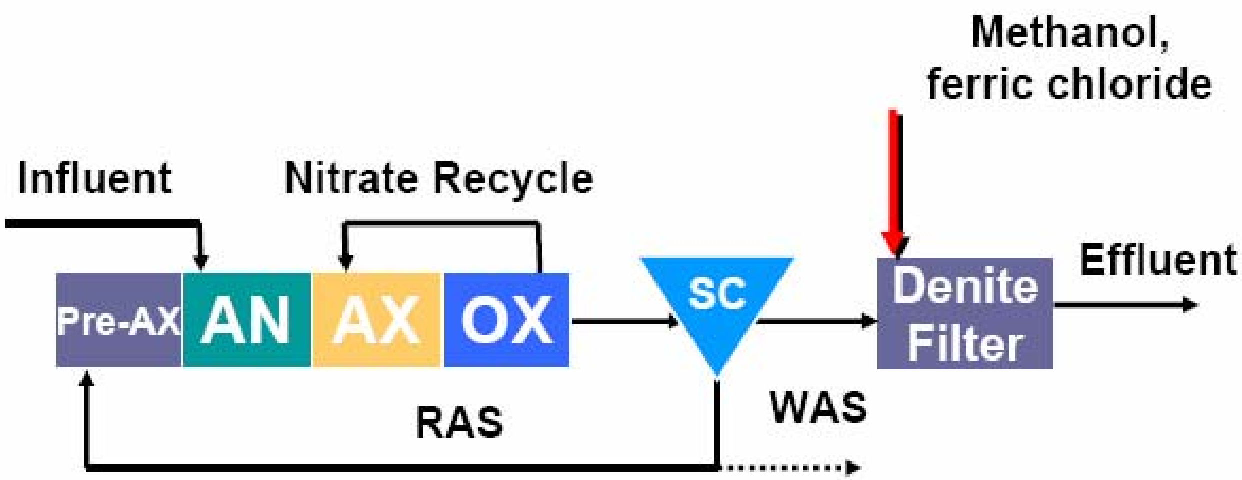
10 mg/L effluent TSS = 1.5 mg/L effluent Total N

Hagerstown WWTP

Johannesburg BNR Process



Add denitrification filters for ENR



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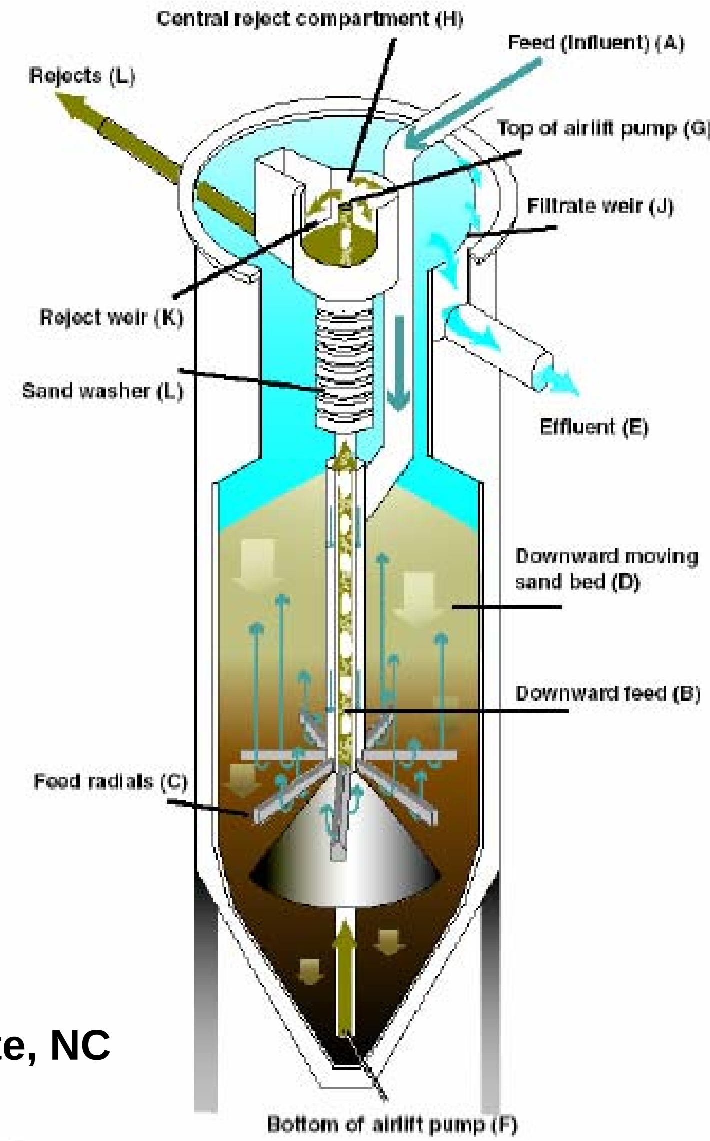
Upflow Continuous Backwash Filters

- Upflow filtration mode
- Sand bed drawn downward into airlift system
  - Media scoured and conveyed to top of bed
- Backwashing continuously at low rate
  - Filter remains in service
- Nitrogen release cycles not required
- Clearwell and mudwell not needed



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Key Technology Issues for ENR

- Ability to meet low TN in downflow denitrification filters is well proven at moderate TP limits (0.5 to 1 mg/L) but not at low TP limits
  - Concerns about phosphorus limitations
- Very little cold weather tertiary denitrification data
- Ongoing WERF study

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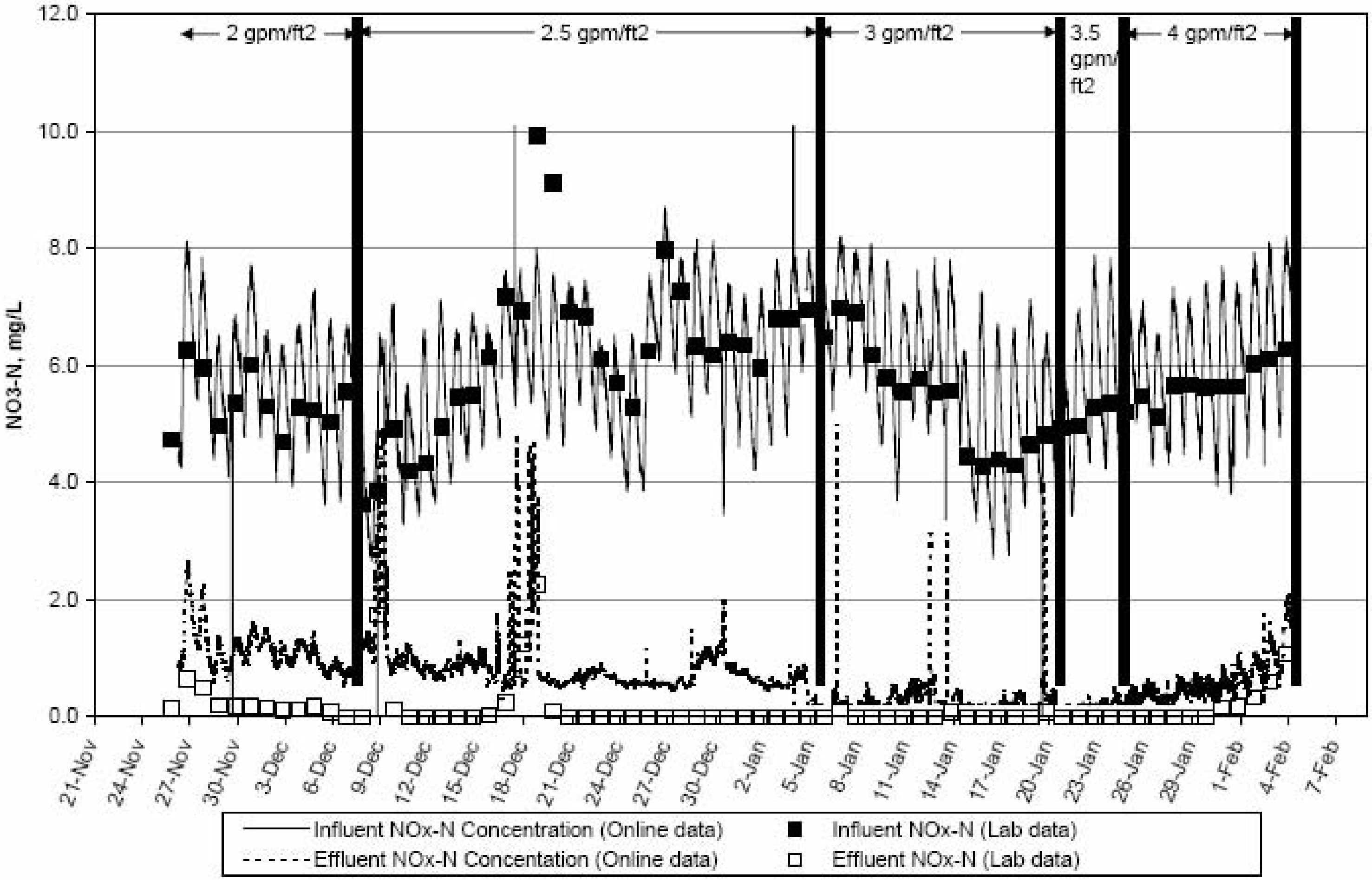
Denitrification Performance During Constant Rate Hydraulic Loading



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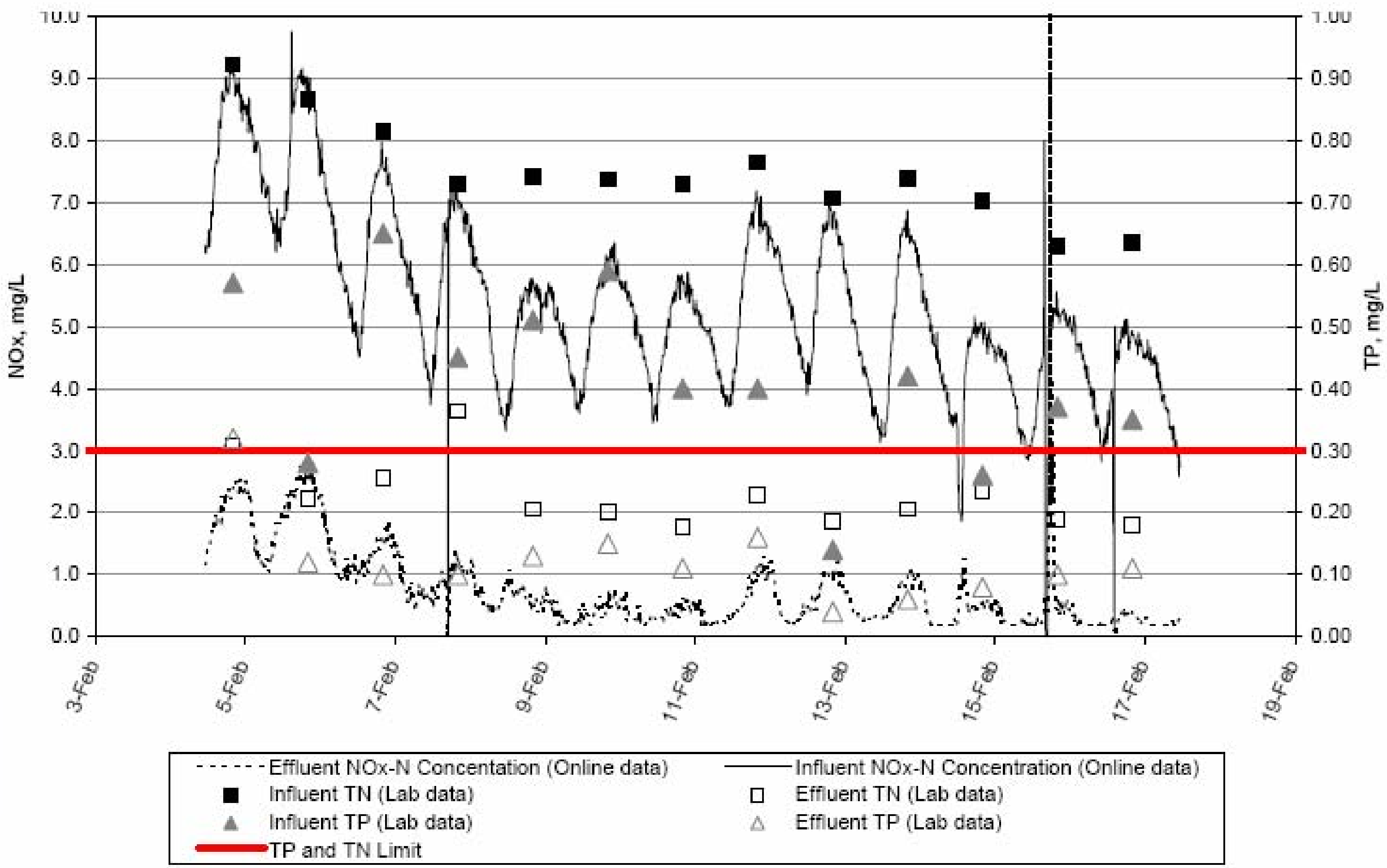
Performance Under Diurnal Flow Variations

Average Hydraulic Loading Rate = 3.5 gpm/ft² with diurnal flow pattern



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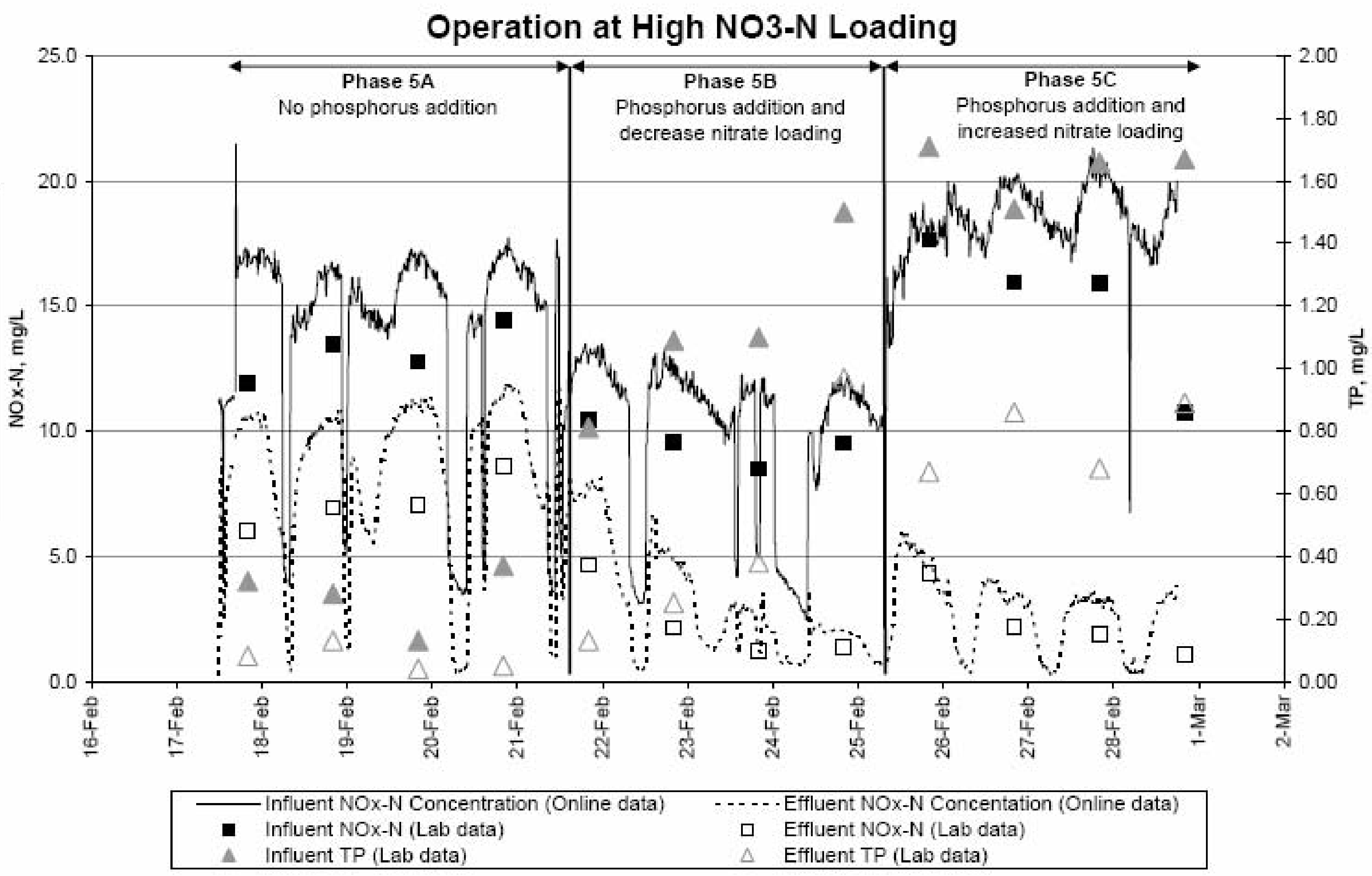
Operation at High Nitrate Loading Rates

Average Hydraulic Loading Rate = 3.5 gpm/ft² with diurnal flow pattern



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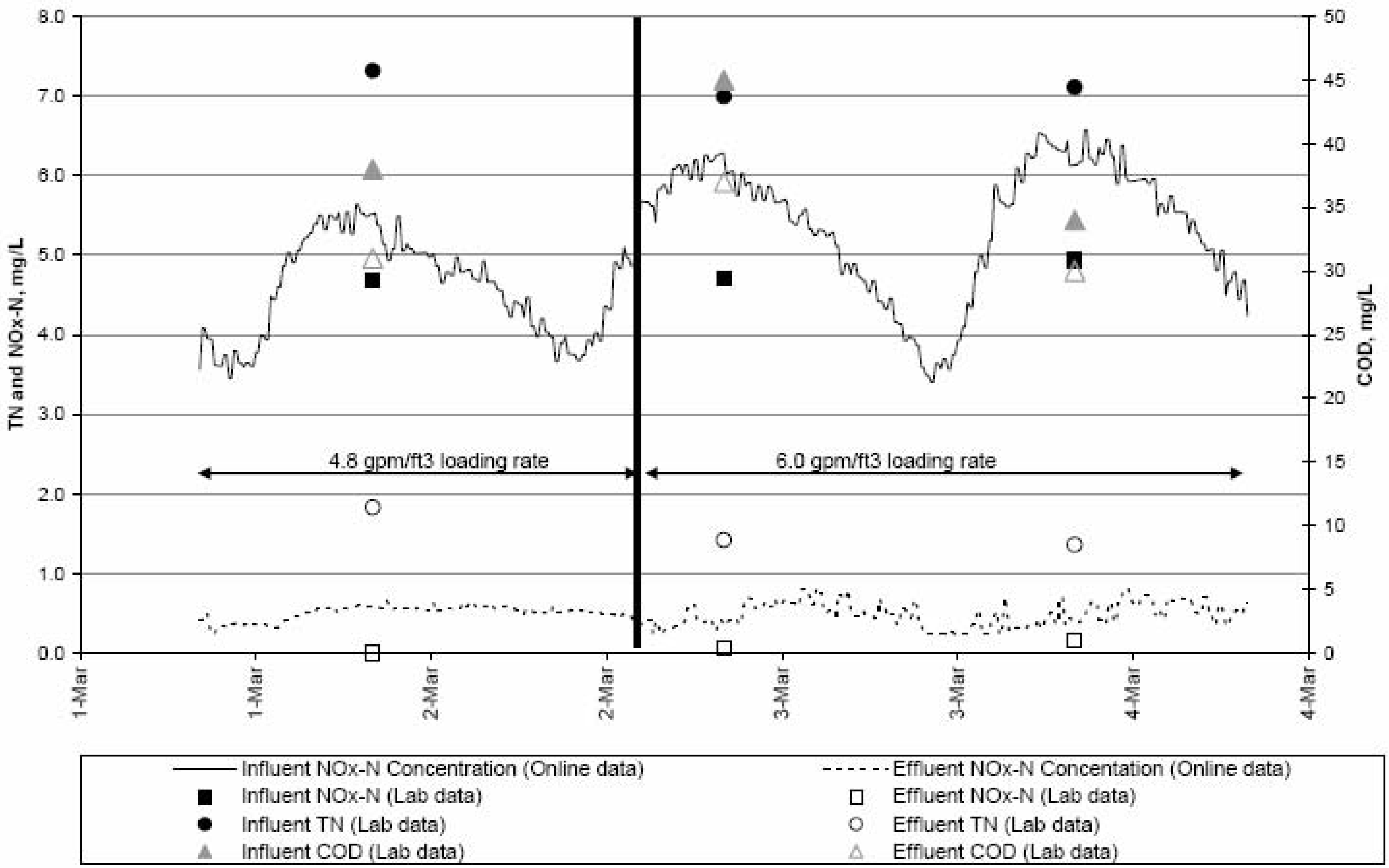
Encountered Phosphorus Limitations at Very High Nitrate Loadings

Denitrification Performance during Peak Hydraulic Loading Conditions

Good dN at short term peak flows



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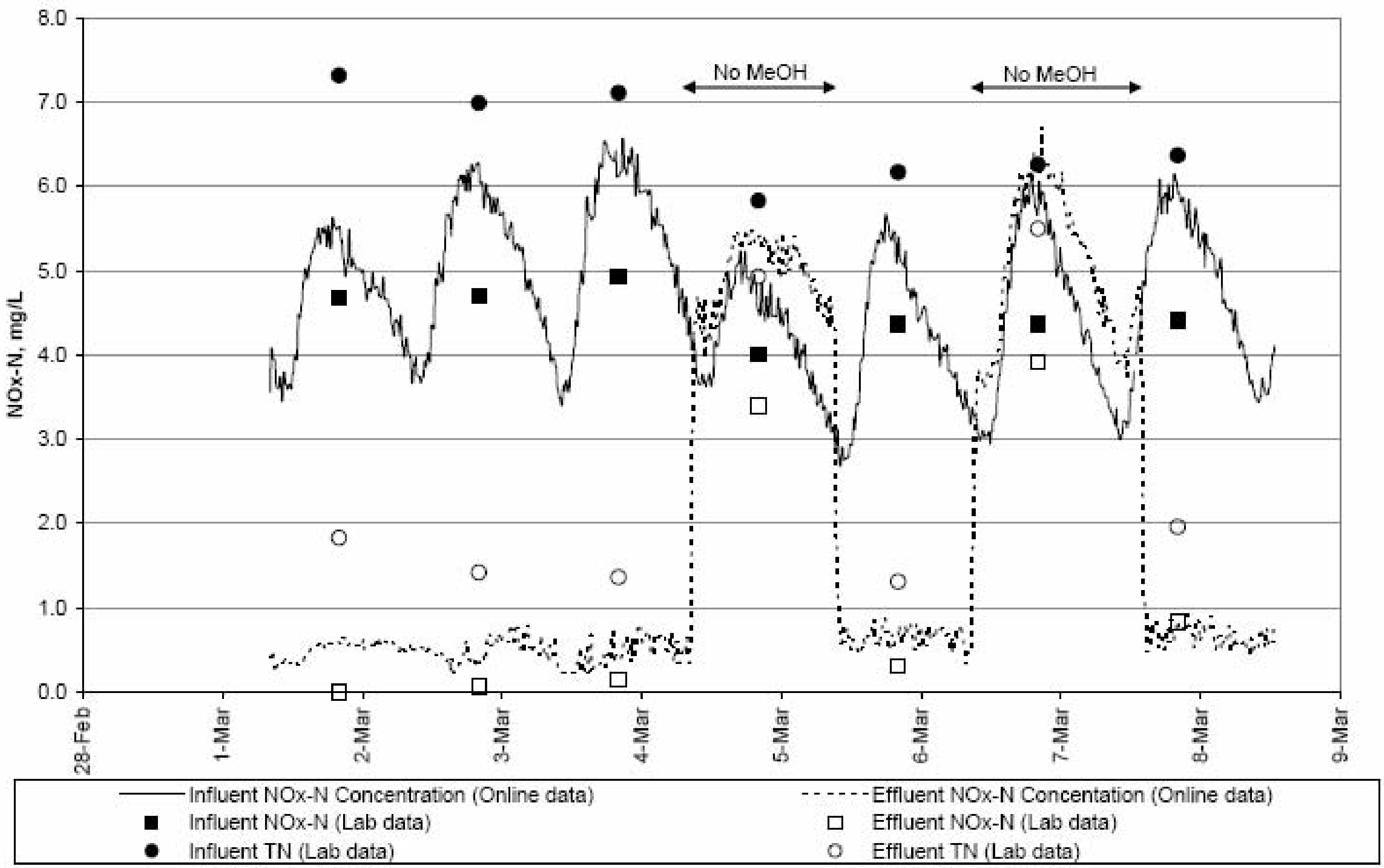
Peak Hydraulic Loading and Recovery of Denitrification



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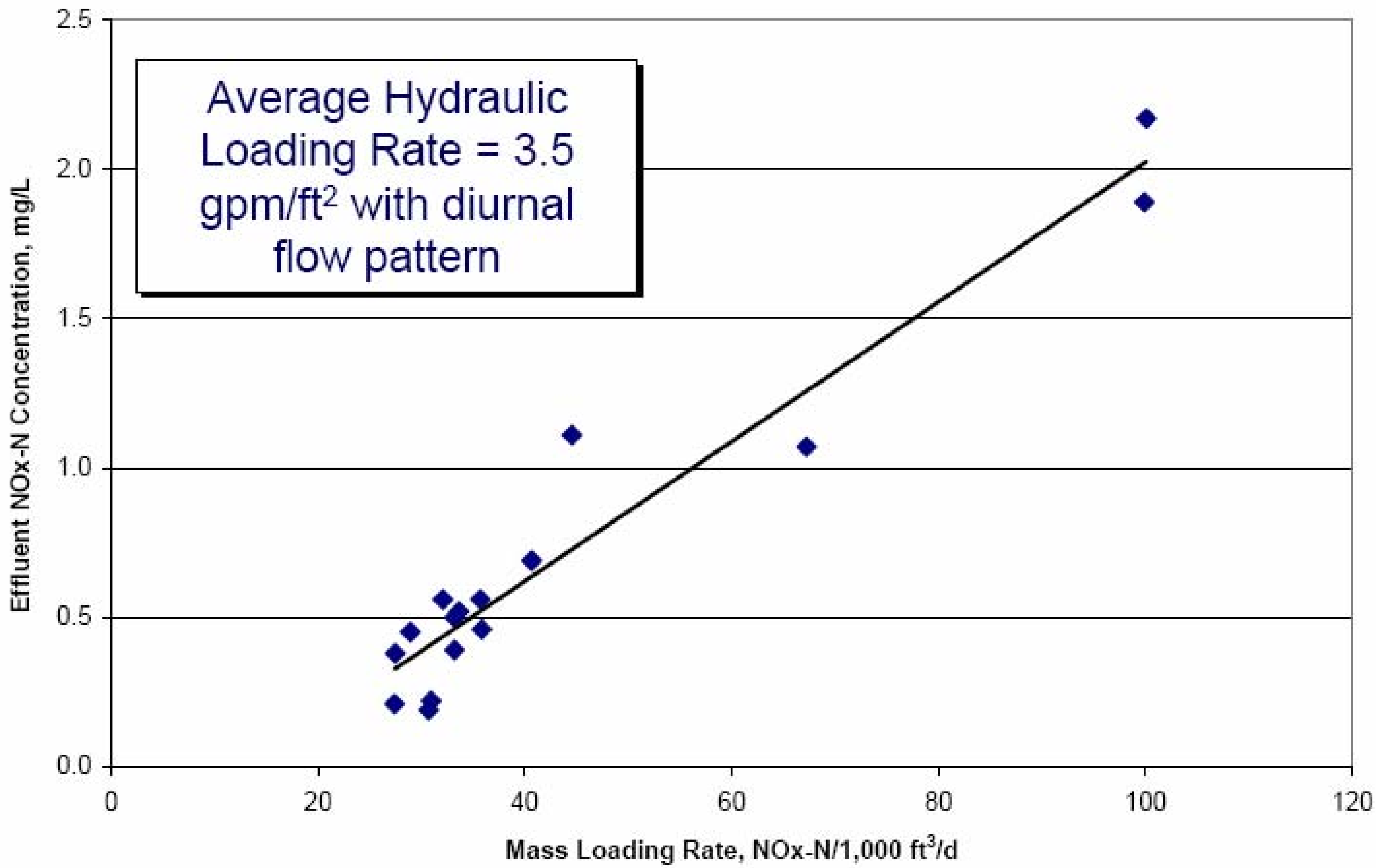
Filter Mass Loading Rate vs. Effluent NOx-N Concentration



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Summary

- Filter met objectives
  - Consistently achieved effluent NOx-N <1 mg/L
  - Simultaneously achieved effluent TP < 0.3 mg/L
  - Methanol dosing ratio consistently in the 2.5 to 3 range
- Design criteria
  - Diurnal hydraulic loading rate of up to 3.5 gpm/ft^2 (max month)
  - Performed well under average mass loading rates up to 100 lbs/1000 ft^3/d at 13 to 15 ^oC
- Phosphorus removal objectives were achieved with direct $FeCl_3$ injection to the filter influent pipe

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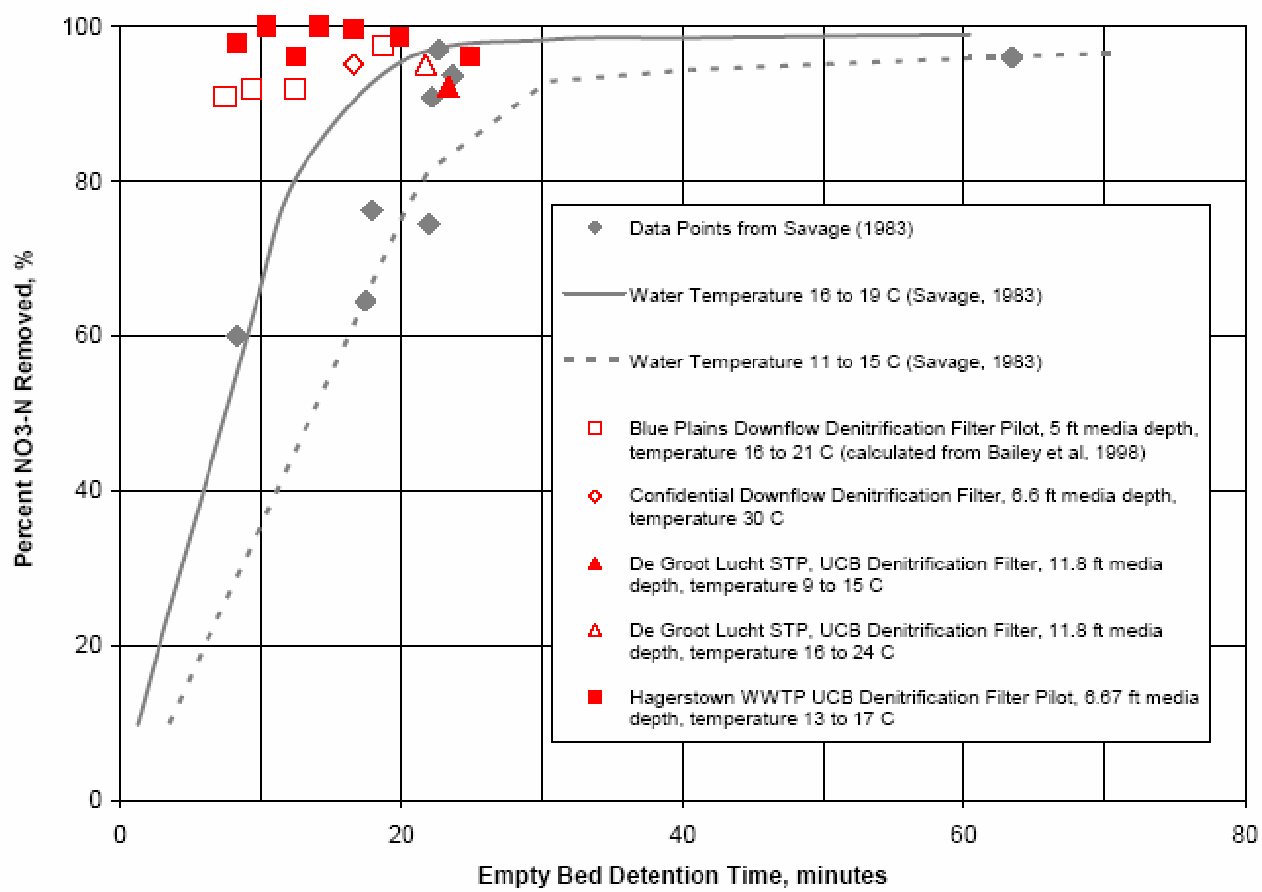
Upflow continuous backwash filters provide enhanced performance for TN removal

Figure 2. Denitrification Filter Design Curves Using Empty Bed Detention Time (from Savage (1983), with Additional Data Points



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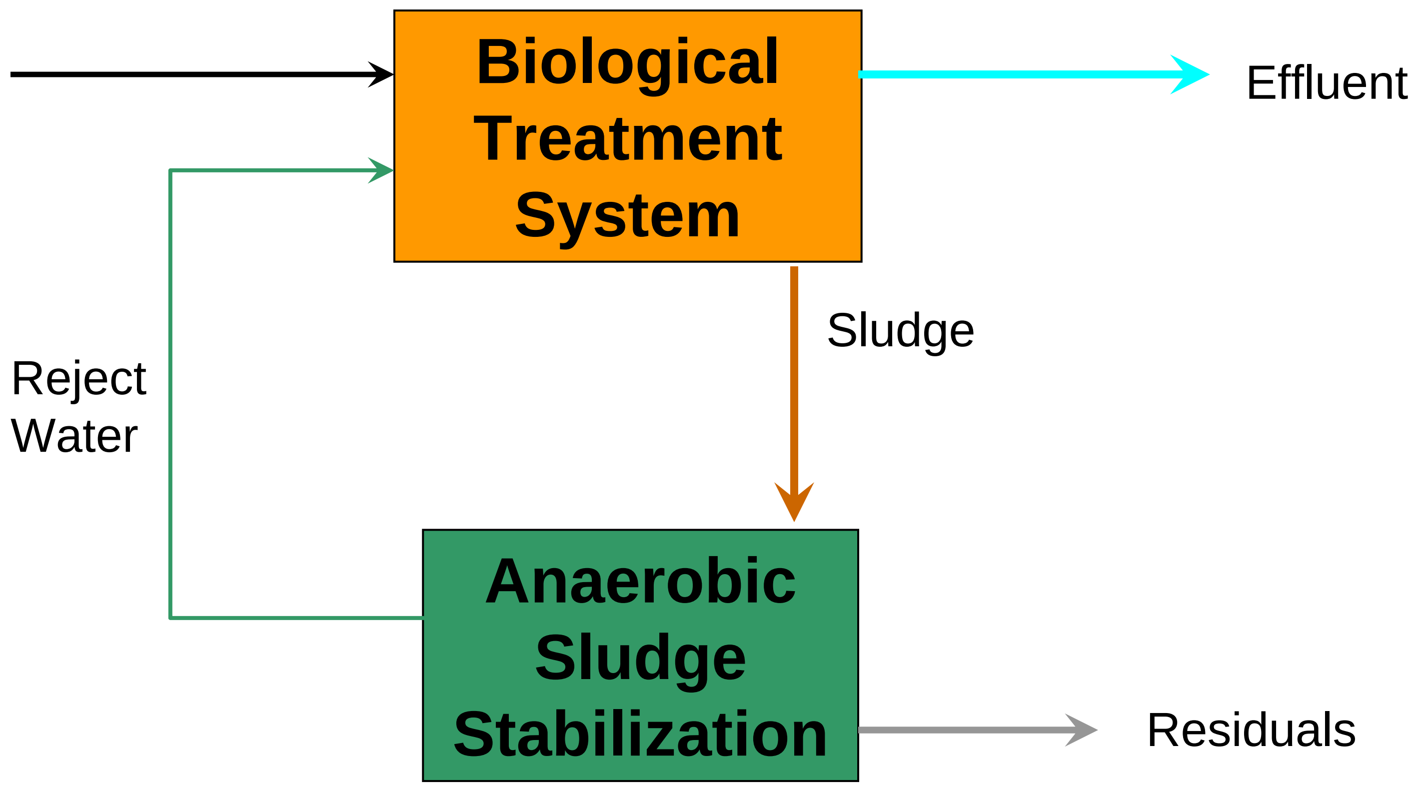
Factors that Affect BNR

- SRT
- Wastewater BOD_5/Nutrient ratios
- Organic matter composition
- Effluent TSS
- Environmental Factors
- - Temperature
- - pH
- - Dissolved O_2 concentration
- Sludge Handling Practices

Consider the impact of reject water on overall N removal capacity of a plant



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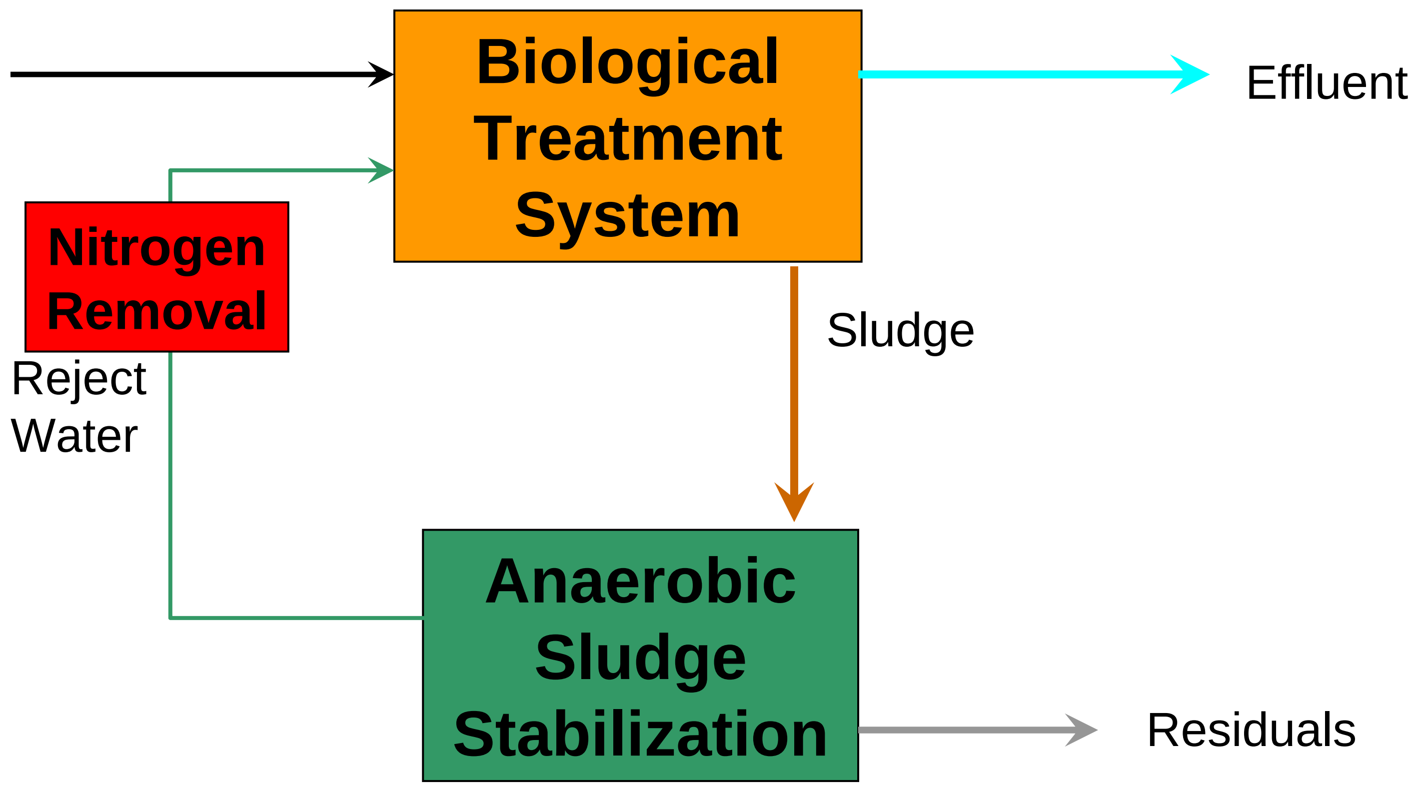
Consider the impact of reject water on overall N removal capacity of a plant



Conventional Nitrification/Denitrification

Aerobic Nitrification

$$NH_4^+ \rightarrow NH_2OH \rightarrow NO_2^- \rightleftharpoons NO_3^-$$

$$NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$$

Anoxic Heterotrophic Denitrification

	Conventional N Removal
COD Input Required (g COD/g N removed)	4.33
O_2 Required (g O_2/g N removed)	4.60
Alkalinity consumption (g $CaCO_3$/g N removed)	3.70
Biomass Formation (g biomass as COD/g N removed)	1.90

Single reactor system for High Ammonia Removal Over Nitrite (SHARON)

Aerobic Nitrification

$NH_4^+ \rightarrow NH_2OH \rightarrow NO_2^- \rightleftarrows NO_3^-$

Anoxic Heterotrophic Denitrification

$NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$

	Conventional N Removal	SHARON
COD Input Required (g COD/g N removed)	4.33	2.60
O_2 Required (g O_2/g N removed)	4.60	3.40
Alkalinity consumption (g $CaCO_3$/g N removed)	3.70	1.85
Biomass Formation (g biomass as COD/g N removed)	1.90	0.76

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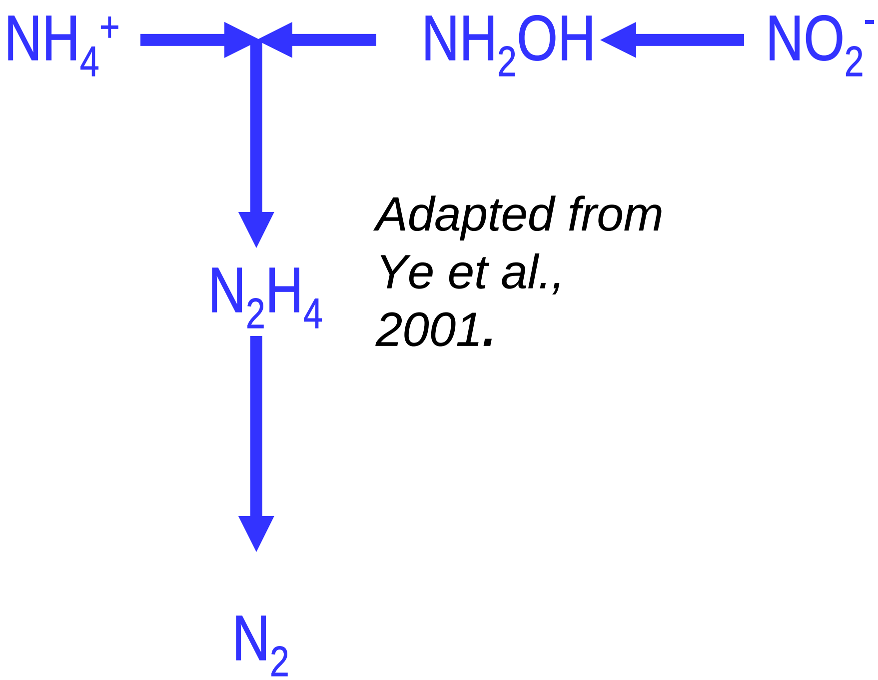
Anaerobic Ammonium Oxidation (ANAMMOX)

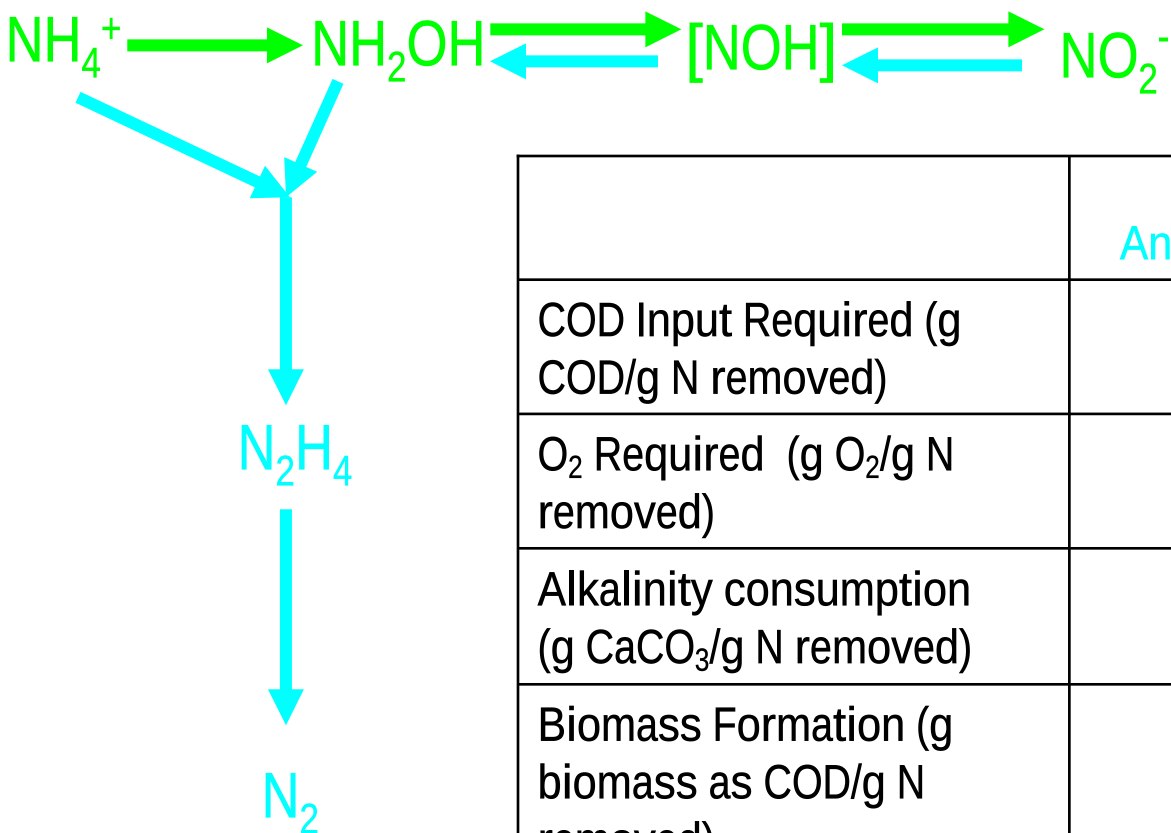


Adapted from Ye et al., 2001.

	Anammox
COD Input Required (g COD/g N removed)	0.00
O_2 Required (g O_2/g N removed)	0.00
Alkalinity consumption (g $CaCO_3$/g N removed)	0.22
Biomass Formation (g biomass as COD/g N removed)	0.08

$$NH_4^+ + 1.30\ NO_2^- + 0.13\ H^+ \rightarrow 1.02\ N_2 + 0.26\ NO_3^- + 2.03\ H_2O$$

Completely autotrophic nitrogen removal over nitrite (CANON)



	Anammox	CANON
COD Input Required (g COD/g N removed)	0.00	0.00
O_2 Required (g O_2/g N removed)	0.00	2.50
Alkalinity consumption (g $CaCO_3$/g N removed)	0.22	0.55
Biomass Formation (g biomass as COD/g N removed)	0.08	0.17

Adapted from Ye et al., 2001.

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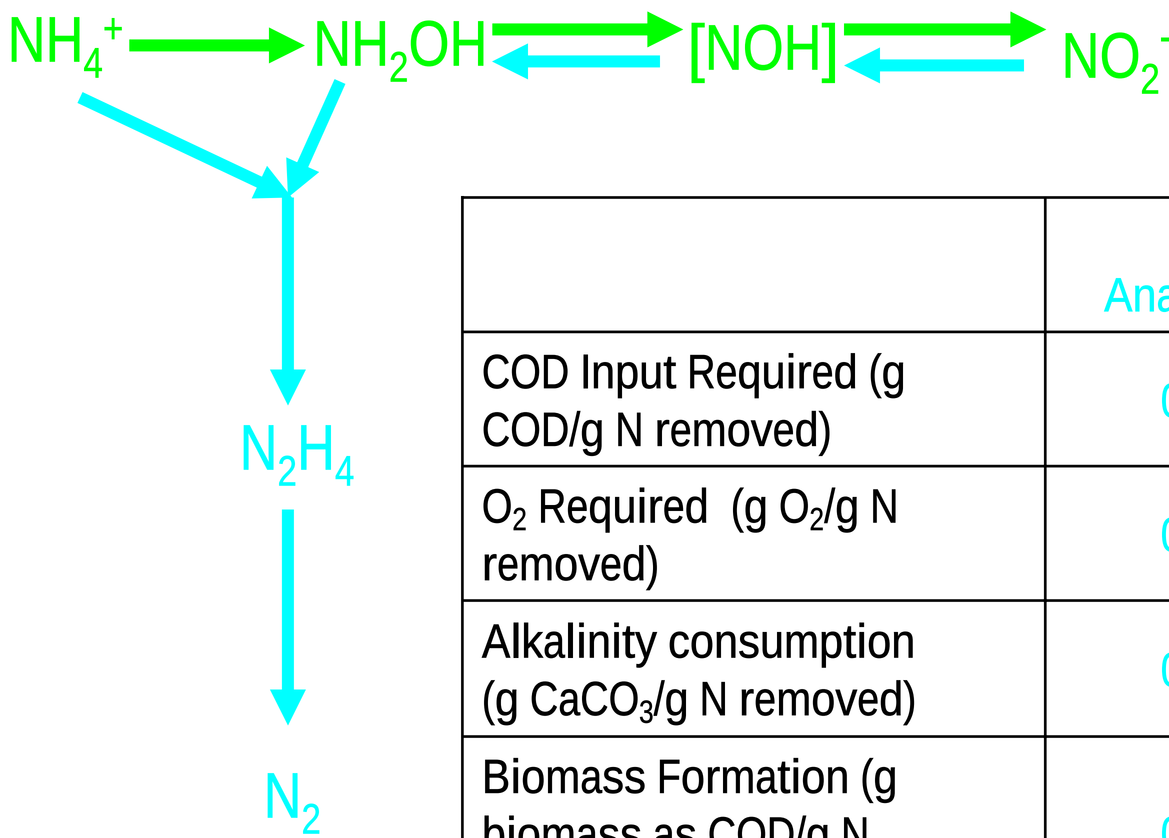
Oxygen Limited Autotrophic Nitrification plus Denitrification (OLAND)



	Anammox	CANON/ OLAND
COD Input Required (g COD/g N removed)	0.00	0.00
O_2 Required (g O_2/g N removed)	0.00	2.50
Alkalinity consumption (g $CaCO_3$/g N removed)	0.22	0.55
Biomass Formation (g biomass as COD/g N removed)	0.08	0.17

Adapted from Ye et al., 2001.

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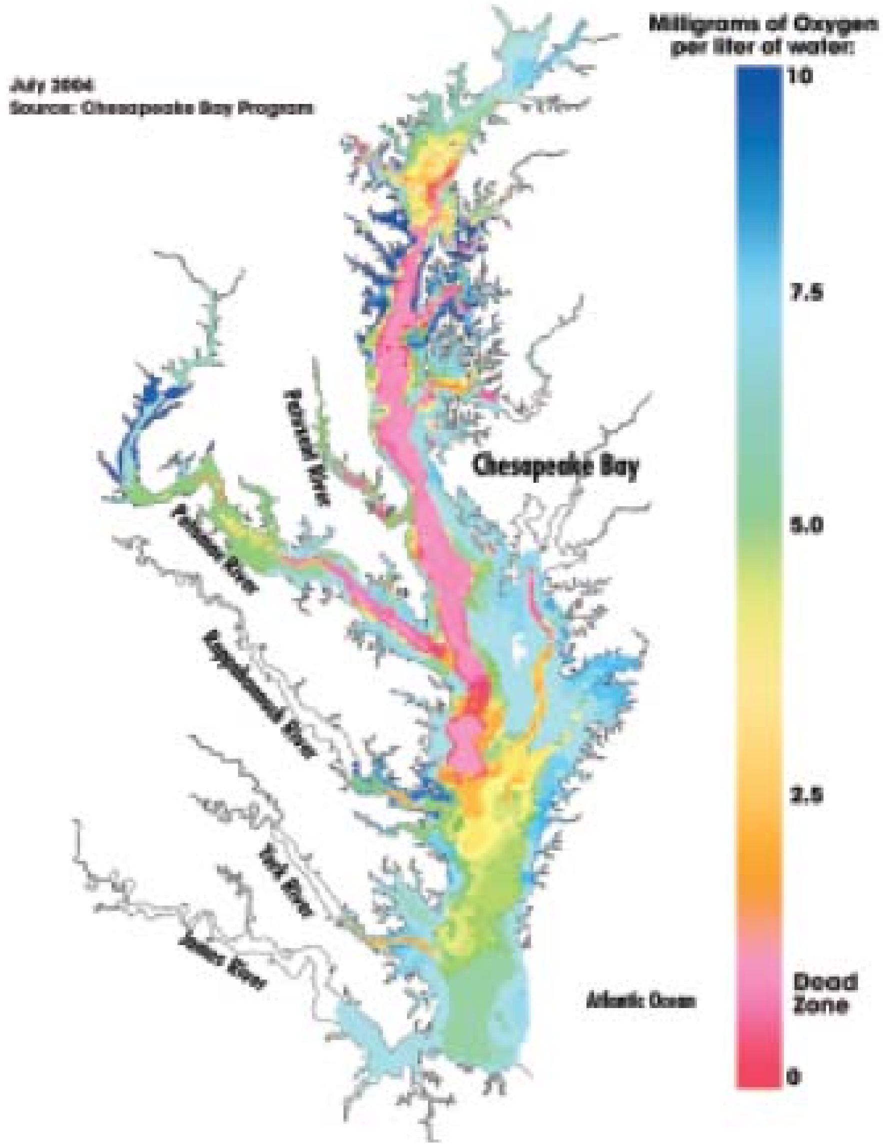
Nitrogen removal is critical to the health of the Bay



35% of the Bay volume was considered to be a “dead zone”

[Chesapeake Bay Foundation State of the Bay 2004]